From prioritizing objects to prioritizing cues

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From prioritizing objects to prioritizing cues:

A developmental shift for cognitive control

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Research Highlights

- A shift in the type of information that children prioritize in their environment may support cognitive control development
- Gaze patterns show preschoolers prioritize objects they can act upon, even if they do not know how to act efficiently, whereas older children and adults prioritize cues signaling how to act efficiently
- Prioritizing cues is associated with better performance in both children and adults

Abstract

Emerging cognitive control supports increasingly adaptive behaviors and predicts life success, while low cognitive control is a major risk factor during childhood, making it essential to understand how it develops. The present study provides evidence for an age-related shift in the type of information that children prioritize in their environment, from objects that can be directly acted upon to cues signaling how to act. Specifically, gaze patterns recorded while 3- to 12-year-olds and adults engaged in a cognitive control task showed that whereas younger children fixated on targets that they needed to respond to before gazing at task cues signaling how to respond, older children and adults showed the opposite pattern (which yielded better performance). This shift in information prioritization has important conceptual implications, suggesting that a major force behind cognitive control development may be non-executive in nature, as well as opening new directions for interventions.

Key words

Cognitive control; executive function; cognitive development; children.

As you eagerly open the box of your new tablet, you get increasingly excited at the prospect of playing with it. Do you start pressing buttons at random to explore what they do, or do you first try to figure out what each button does (e.g., from the user-guide)? These two approaches may depend on what you prioritize in the environment: the objects that can be acted upon, or the information signaling how to act efficiently. The present paper reports evidence that, though there may be individual preferences, the type of information that people prioritize shifts during childhood, profoundly impacting the development of cognitive control.

The emergence of cognitive control—the goal-directed regulation of thoughts and actions—during childhood supports greater autonomy and increasingly adaptive behavior. Children's cognitive control is one of the best predictors of later academic achievement, income, and health (e.g., Daly, Delaney, Egan, & Baumeister, 2015; Moffitt et al., 2011), and develops in a protracted fashion that mirrors the development of the prefrontal cortex (e.g., Moriguchi & Hiraki, 2013). It relies on progressive differentiation of major components of control (working memory updating, response inhibition, set-shifting; e.g., Lee, Bull, & Ho, 2013), and increasing efficiency of these components (e.g., Best & Miller, 2010), alongside qualitative changes allowing more optimal control adjustment as a function of goals and related task demands (e.g., control strategy or control mode selection; Ambrosi, Lemaire, & Blaye, 2016; Chevalier, 2015; Yuko Munakata, Snyder, & Chatham, 2012).

Goals in working memory –the intention to perform an action achieve a task, or reach a state (Altmann & Trafton, 2002)—play a central role in cognitive control by guiding actions (Miller & Cohen, 2001). Children often particularly struggle to identify the goals that they need to reach, resulting in poor cognitive control (see

Chevalier, 2015). Goals are often signaled by cues in the environment (e.g., a red light signals the need to stop, a puzzled face the need to explain something, a nudge the need to start talking, etc.). Children, especially preschoolers, struggle to process environmental cues. However, they show improved cognitive control performance on tasks that require inhibiting a prepotent response or switching between tasks when the processing of such cues is facilitated (e.g., Barker & Munakata, 2015; Blaye & Chevalier, 2011; Chevalier & Blaye, 2009; Chevalier, Huber, Wiebe, & Espy, 2013) or after practicing rapid cue processing (Chevalier, Chatham, & Munakata, 2014). Although cue processing in control-demanding contexts improves with age (Chevalier & Blaye, 2009; Chevalier et al., 2013), it remains a major challenge in adults (Chatham et al., 2012). Importantly, increasingly efficient processing of cues such as head orientation, body posture, or eye movement help infants follow an adult's gaze, (Corkum & Moore, 1998; Gregory, Hermens, Facey, & Hodgson, 2016), speaking to its broad role in cognitive development.

As children pick up increasingly subtle environmental cues with age, they more efficiently identify goals and use them to control their thoughts and actions (e.g., they may infer they need to clean up their room from a glare from parents instead of needing a verbal reprimand). A key question, however, is how cue processing improves with age. We propose that children pay greater attention to cues with age, supporting increasingly successful goal identification (sometimes referred to as task selection or rule inference). Specifically, early in childhood, children may prioritize processing information or objects in the environment that they can directly act upon/manipulate, even though they do not know how to manipulate them efficiently. Later in development, and with the increasing need for autonomy, children may progressively prioritize information (cues) that signal how to act/manipulate objects efficiently, hence facilitating goal identification and thus goal-directed behavior.

Such a shift in information prioritization could be adaptive throughout childhood. Immature cognitive control may be advantageous in early childhood because without the specific constraints of a goal, children can more freely explore their environment. This could aid the learning of statistical regularities which in turn support cognitive acquisitions such as language and social conventions (Chrysikou, Weber, & Thompson-Schill, 2013; Thompson-Schill, Ramscar, & Chrysikou, 2009). This lack of bias by existing knowledge (which constrains information interpretation) and goals (which restrict possible behaviors) may help children learn statistical regularities better than adults (Gopnik, Griffiths, & Lucas, 2015). Consistently, children explore novel objects and discover more of their functions when they are not given specific instructions of how to use them (Bonawitz et al., 2011). Prioritized processing of objects that can be manipulated over cues signaling how to use them may indeed support such bottom-up, data-driven behaviors. In contrast, as learning statistical regularities becomes less crucial and the need for autonomy and efficient behavior grows with age, top-down control becomes more adaptive (Thompson-Schill et al., 2009), and may be facilitated by prioritizing environmental cues in later childhood.

We test the hypothesis of a shift in information prioritization during childhood by examining three- to 12-year-olds' and adults' gaze patterns as they engage cognitive control in a cued task-switching paradigm, in which performance improves as children get older (Carlson, 2005; Cepeda, Kramer, & Gonzalez de Sather, 2001; Zelazo, 2006). Participants switched back and forth between matching a target picture (e.g., a pink teddy bear) with the response picture of the same shape or color, as a function of visual task cues (color patches for color-matching and toy outlines for shape-matching) (Figure 1). If the type of information prioritized shifts during childhood, then gaze patterns should change too. Specifically, younger children should fixate the target (i.e., the object they have to respond to) before the cue (i.e., the information signaling how to respond efficiently to the target), whereas older children, like adults, should gaze at the cue before fixating the target.

Method

Participants

Participants included 72 three- to 12-year-old children (*M* = 7.6 years, *SD* = 2.6, range: 3.6-12.7, 39 females) and 26 adults (*M* = 23 years, *SD* = 3.5, range: 18-31, 15 females). All participants were recruited from the community through adverts. They were predominantly Caucasian and from middle to high socioeconomic status, reflecting the characteristics of the local community, although demographic information was not collected. Informed written consent was obtained from children's parents and from adult participants, and all children provided verbal assent. Parents and adult participants received £5 compensation for their time and travel costs, and each child received a small, age-appropriate prize.

Materials and Procedure

All participants were tested individually in the lab by a trained experimenter in a 30-min. session. They completed a child-friendly, cued task-switching paradigm (adapted from Zelazo, 2006 and Meiran, 1996, and presented with E-Prime 2; Psychology Software Tools, Pittsburgh, PA) in which Santa needed help sorting toys for Christmas. Participants had to switch back and forth between matching a bidimensional target (a pink teddy bear or a blue car) with the response picture of the same color or the same shape, as a function of a visual task cues (four patches of color for color-matching and four outlines of toys for shape-matching) (Figure 1). The two response pictures (a blue teddy bear and a pink car) were constantly visible on the right- and left-hand sides of the monitor. Children entered their responses by pressing two buttons on a gamepad. Each trial started with a fixation cross at the center of the monitor. After 1000ms, the fixation cross disappeared while the target and the cue were simultaneously displayed at the top and bottom center of the monitor, at equal distance from the fixation cross and the two response options. The locations (top or bottom) of the target and cues were counterbalanced across participants to ensure gaze patterns were not simply driven by spatial arrangements (e.g., always looking first at the top of the screen). Targets and cues remained on screen until a response was entered and were then replaced with centrally located feedback for 500ms. Feedback either comprised a picture of Santa Claus along with a Christmas bell sound (correct responses) or a picture of a reindeer and the sound "no!" (errors).

Children first completed two single-task blocks (one color, one shape), each comprising 4 warm-up trials followed by 9 test trials. The order of the color- and shape-matching tasks was counterbalanced across participants. Within each single-task block, the same task was relevant across all trials, making it unnecessary to process the task cue. Children then completed a mixed-task block where they had to switch between the two tasks unpredictably as a function of the cue. There were 6 warm-up trials and two series of 22 test trials separated by a short break. The test trials (total 44) included 14 switch trials, where the relevant task changed from the previous trial (e.g., a color trial following a shape trial), 28 no-switch trials, where the relevant task repeated (e.g., a color trial following another color trial), and two start trials. Due to task uncertainty, participants had to process the cue on each trial within mixed-task blocks to identify the relevant task and process the target accordingly, whether or not the relevant task actually changed (switch trials) or repeated (no-switch trials). Guidance was provided on warm-up trials, which could be repeated if needed, but not on test trials.

Participants' right eye position was remotely tracked with an EyeLink 1000 eye-tracker (SR Research, Ottawa, Canada) using a 500Hz-sampling rate. A 5-point calibration procedure was conducted before starting the task. Fixations longer than 40ms falling on either the task cue or the target were compiled for each trial. Trials were categorized into five gaze patterns as a function of the order in which these areas of interest were fixated: (1) *Cue-Target*: the cue was fixated before the target; (2) *Target-Cue*: the target was fixated before the cue; (2) *Target-Only*: only the target was fixated (not the cue); (4) *Cue-Only*: only the cue was fixated (not the target); and (5) *Other*: all other patterns (e.g., only the location of the fixation cross, only the response options, etc.).

With the aim of detecting developmental trends in the probability of occurrence of these five patterns during childhood, we fitted a multinomial generalized model with the patterns as categorical dependent variable and age in interaction with item type as explanatory variables using the net library (Venables & Ripley, 2002) in R (R Foundation for Statistical Computing, Vienna, Austria). This model allowed us to compute predictions used for graphical representations purposes. However, local dependencies in the data due to subject nesting led us to adopt a random effect approach to draw inferential conclusions. As multinomial random effect models are not yet available in the standard statistical library, we used a one vs. rest heuristic approach, as suggested by Agresti (2002). We modeled the probability of one given gaze pattern or using any of the other ones with binomial random effect models. Models including age or not were compared with a likelihood ratio test

(LRT) to obtain the probability associated to the developmental trend for this gaze pattern. In adults, the model was simpler as it did not include age, and gaze pattern probabilities were thus examined with a more straightforward approach using a mixed effect model with a Poisson distribution. This approach modeled the frequency of each gaze pattern for each participant and each trial type (Faraway, 2006). Response times and accuracy were examined with general linear models, after log-transforming response times (to correct for skewedness) and removing outliers lower than 200 ms or greater than 3 standard deviations above the mean, calculated separately for each trial type and four age bands, 3-5 years, 6-8 years, 9-12 years, and adults (1.4% of trials were removed overall).

Results

Response times and accuracy

Separate general linear models were used to examine the effects of trial type (discrete) and age (continuous) on response times and accuracy in children, and the effect of trial type in adults. Log-transformed response times and accuracy significantly varied across trial types for both children, $F(2, 140) = 217.29$, $p < .001$, and $F(2, 140) = 35.41$, $p < .001$, and adults, $F(2, 50) = 268.8$, $p < .001$, and $F(2, 50) = 10.41$, $p < .001$, and interacted with children's age, $F(2, 140) = 4.79$, $p = .009$, and $F(2, 140) = 10.75$, $p < .001$ (Figure 2). Consistent with increasing task-identification demands, responses were slower and less accurate on no-switch trials of the mixed-task blocks than on single-task blocks in both children (7.5 vs. 6.8 ln ms and .84 vs. .90, *p*s < .024) and adults (6.9 vs. 6.2 ln ms and .93 vs. .97, *p*s < .047). Having to switch tasks yielded longer response times and lower accuracy in both children (7.7 ln ms and .74, *p*s < .018) and adults (7.1 ln ms and .88, *p*s < .018). The difference in accuracy between single-task blocks and no-switch trials reduced with children's advancing age whereas surprisingly the difference in response times increased with age (this was no longer significant when including only children who responded greater than chance—see below), *p*s = .002. Age did not affect the magnitude of the additional performance drop on switch trials relative to no-switch trials, *p*s > .116, suggesting that developmental changes in performance are tied to increasingly efficient task identification rather than changes in switching tasks per se.

Gaze patterns

Gaze patterns for each trial were categorized as a function of whether participants fixated the cue before the target (*Cue-Target*), the target before the cue (*Target-Cue*), the cue but not the target (*Cue-Only*), the target but not the cue (*Target-Only*), or fixated neither area of interest (*Other*)[1]. These patterns are shown in Figure 3. For both children and adults, *Target-Only* patterns were much more frequent than the other patterns in single-task blocks, LRT: $\chi^2(4) = 128.9$, $p < .01$, which is unsurprising given that there was no task uncertainty in these blocks and thus no need to gaze at the cue. In contrast, on most trials of the mixed-task blocks, adults started with the cue before turning to the target, with the *Cue-Target* pattern being much more frequent than the *Target-Cue* pattern during both the switch and the no-switch trials, LRT: $\chi^2(4) = 32.4$, $p < .01$. The youngest children, however, showed a majority of *Target-Only* patterns in the mixed-task blocks, not looking at the cue at all. This could reflect extreme prioritization of targets over cues, or alternatively suggest that these children simply did not understand task instructions. We therefore excluded all the children (n=12) with accuracy performance not significantly above chance in these blocks (based on the binomial distribution); these children were all between 3

[1]Because the number of valid trials was significantly correlated with children's age, $r = .351$, $p = .002$, we also ran models including that variable and observed the same age effects, hence changes in gaze patterns during childhood are not a mere byproduct of increasing number of valid trials with age.

and 5 years of age and did not differ in mean age or gender ratio from the remaining 14 children within this age range, *p*s > .404. In the remaining children, patterns including only the targets were less frequent, further suggesting these children understood task instructions.

Across childhood we found a developmental change in focus from target to cue. Critically, in early childhood, participants prioritized the target over the cue, whereas later in childhood they prioritized the cue over the target, similarly to adults. Specifically, *Target-Cue* patterns progressively decreased with age, LRT: $\chi^2(1) = 19.9$, $p < .001$, whereas *Cue-Target* patterns progressively increased until they became the most frequent patterns, LRT: $\chi^2(1) = 28.8$, $p < .001$, with the shift occurring around 8.5 years of age. Furthermore, when fixating only one of the two areas of interest, young children mostly gazed at the target, whereas older children, like adults, favored the cue, as shown by the decrease in *Target-Only* patterns, LRT: $\chi^2(1) = 29.4$, $p < .001$, and increase in *Cue-Only* patterns with age, LRT: $\chi^2(1) = 18.9$, $p < .001$.

Performance associated with gaze patterns

Finally, to directly examine whether fixating the cue before the target actually yielded a performance advantage, we ran two general linear models with age group (children, adults) and gaze pattern (Cue-Target, Target-Cue) as predictors to compare response accuracy and response times associated with *Cue-Target* and *Target-Cue* gaze patterns in the mixed-task blocks. Both children and adults performed better when fixating the cue first (Figure 4). Specifically, response accuracy was greater for *Cue-Target* than *Target-Cue* patterns (.92 vs. .87), $F(1, 237) = 5.29$, $p = .022$. For response times, there was a significant interaction with age, $F(1, 225) = 5.13$, $p = .024$. Children responded faster when they engaged in *Cue-Target* than *Target-Cue* patterns (7.6 vs. 7.8 ln ms, $p < .001$), whereas no difference was observed in adults ($p = .435$).

Discussion

The information that children prioritized in the task shifted during childhood from targets that they had to respond to, to cues signaling how to respond. Specifically, young children either fixated the target before the cue, or even just the target, even though the cue was the only indicator to allow them to successfully complete the task. This pattern progressively reversed and after 8.5 years, children mostly fixated the cue before the target or even just the cue, which is strikingly similar to mature gaze patterns in adulthood. Cue prioritization denoted more efficient cognitive functioning, as shown by faster and more accurate responses relative to target prioritization.

Response times and accuracy showed that developmental change was largely driven by a reduction in the cost of task mixing (i.e., single-task block trials vs. no-switch trials), which indexes the difficulty of identifying the relevant task when tasks are mixed. In contrast, the cost of task switching per se (i.e., no-switch vs. switch trials) did not vary significantly with age. These findings confirm that goal identification is a major force driving cognitive control development. Further, gaze patterns revealed that children's difficulty with goal identification stems from a tendency to overlook environmental cues in favor of objects that can be acted on. Consistently, relative to older children, preschoolers have been found to more often label the target or the response and less often the cue, when they are asked to "think aloud" (Karbach & Kray, 2007), and to perform better when encouraged to process the cue before the target (Chevalier, Martis, Curran, & Munakata, 2015).

Alternatively, one may argue that changes in metacognitive reflection on cognitive control, such as increases in reflective reprocessing of information (Zelazo, 2004), may lead children to approach the task differently, resulting in different gaze patterns with age. For instance, children may gain a better understanding of the advantage of processing the cue first with age, accounting for the progressive increase in *Cue-Target* patterns with age. However, such an account, which is consistent with recent findings pointing out the role of metacognition in cognitive control development (Chevalier & Blaye, 2016; Chevalier et al., 2015), would not be mutually exclusive with a shift in environmental information prioritization, as changes in information prioritization may support metacognitive gains and vice-versa.

The mechanism by which children pay increasing attention to cues with advancing age remains a major question. One possibility is that children learn to associate object or contextual features with specific actions or functions through mere exposure and statistical learning. Over time, children may learn to use these associations to predict how to behave efficiently when they encounter similar contextual or object features, which now serve as cues. Thus, children may pay increasing attention to cues whose meaning and predictive value they have learnt. Indeed, similar cue-action association learning seems to underpin the development of joint visual attention during infancy (Corkum & Moore, 1998), and gaze cueing in childhood and adulthood (Cole, Smith, & Atkinson, 2015; Gregory et al., 2016; Guzzon, Brignani, Miniussi, & Marzi, 2010). Although speculative, this account suggests that a mechanism of change based on cue-action association learning, which is not executive in nature, may profoundly impact on cognitive control during childhood.

In particular, the shift in information prioritization may contribute to the age-related shift from reactive to proactive control, which shows a similar developmental trajectory. Younger children tend to engage control reactively, that is, the moment that they process potential conflict among multiple responses (e.g., improvising during a class presentation). On the other hand, older children and adults engage proactive control, anticipating and preparing for conflict before it arises (e.g., gathering thoughts before a class presentation) (Chatham, Frank, & Munakata, 2009; Lucenet & Blaye, 2014; Munakata, Snyder, & Chatham, 2012). A shift in information prioritization could directly support the transition to proactive control. Specifically, associative learning of the meaning and predictive value of cues may lead children to increasingly prioritize this information, which in turn supports anticipatory use of cues to reliably predict not just how to behave, now but also how to proactively prepare for upcoming events.

The shift in information prioritization has major theoretical and practical implications. At the theoretical level, not only does it reveal an important factor that may affect cognitive control development, but it also suggests that this development may be driven, at least in part, by a change that is not executive in nature. Instead, progress in cognitive control may result from mere exposure to and learning about the environment, with this accumulating knowledge being used to better identify goals and guide actions. Reciprocally, this accumulating knowledge may prompt children to more actively monitor for relevant cues and learn about new cues in the environment. This is in stark contrast with traditional conceptualizations of cognitive control development as exclusively or mainly relying on incremental changes in executive abilities per se. At the practical level, it opens radically new routes for interventions, suggesting that cognitive control could be improved by training children to learn about and look for cues that are predictive of the most appropriate actions. This new route for interventions is especially important given that extant training programs focusing on executive processes per se have met with mixed success, and indeed, training focused on increased attention to relevant cues has already proven successful in middle childhood (Chevalier et al., 2014).. Designing effective interventions is crucial as low cognitive control is pervasive in learning disorders and atypical development, and is a major risk factor for academic failure and cascading negative outcomes.

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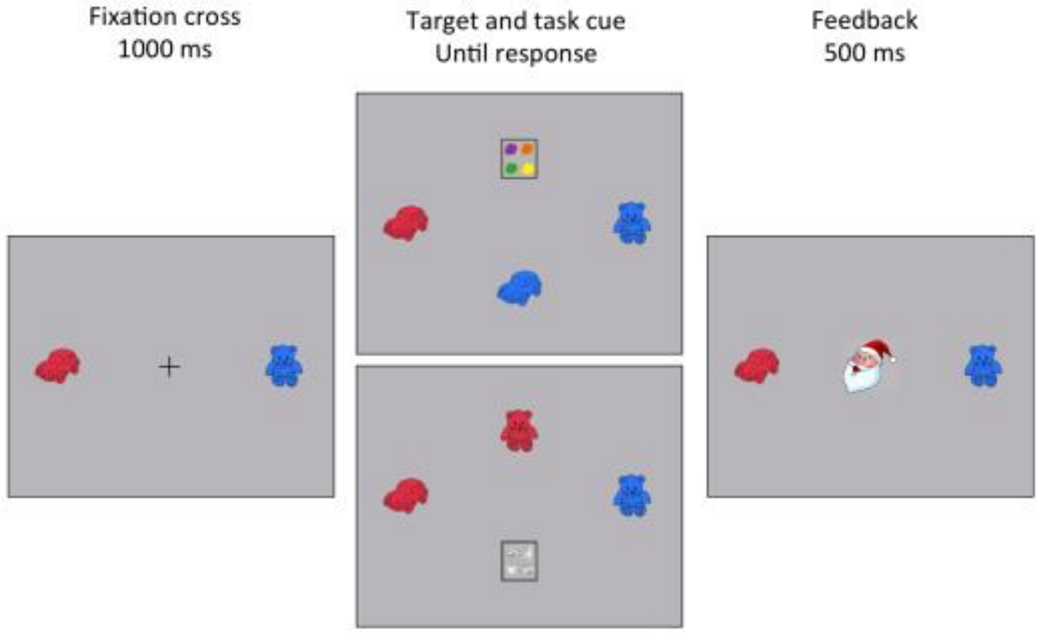

Figure 1. Cued task-switching paradigm ("Santa Game"). Participants had to match the target (center) with the response picture (sides) of the same shape or the same color, as a function of the task cue (center). Vertical arrangement of the target and task cue was counterbalanced across participants. Each trial started with a 1000-ms fixation cross, which disappeared as the target and task cue were simultaneously displayed until a response was entered. Feedback was then presented for 500 ms (either Santa after correct responses or a reindeer after errors).

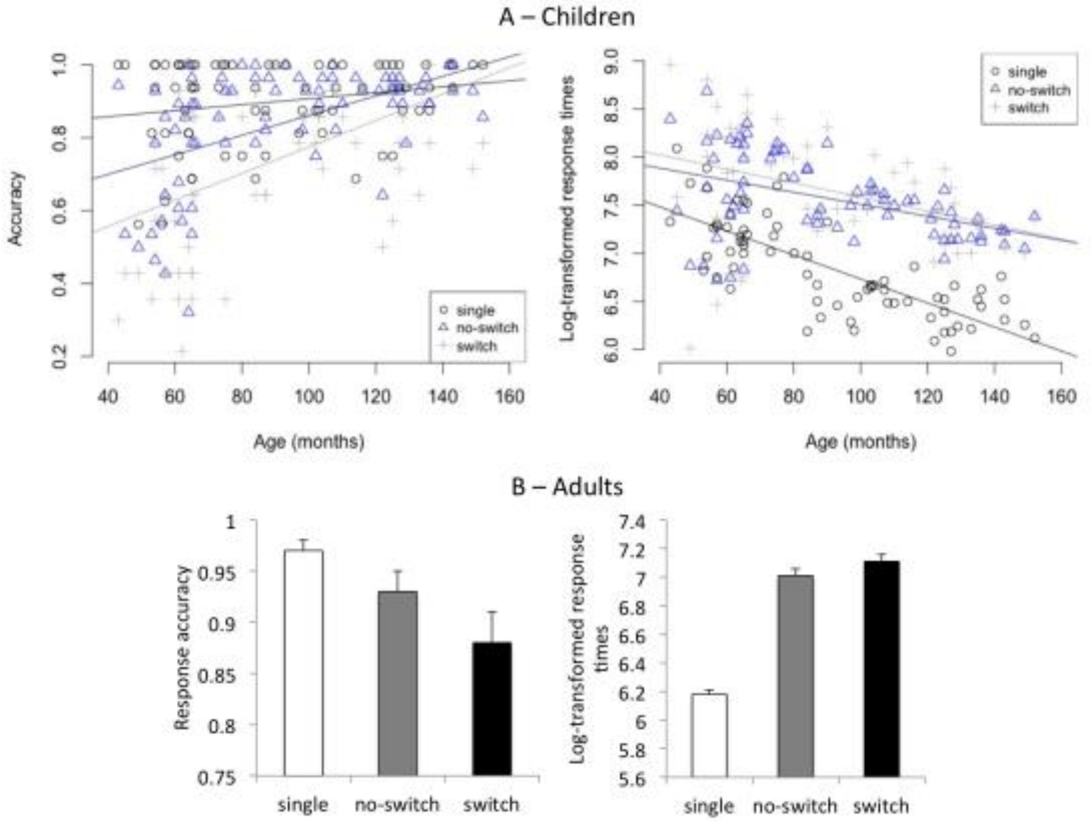

Figure 2. Response accuracy and log-transformed response times for children (A) and adults (B) for single-task block, no-switch, and switch trials. Error bars represent standard errors. Both children and adults showed a performance decrement related to task mixing and task switching. Only task mixing costs varied with age during childhood.

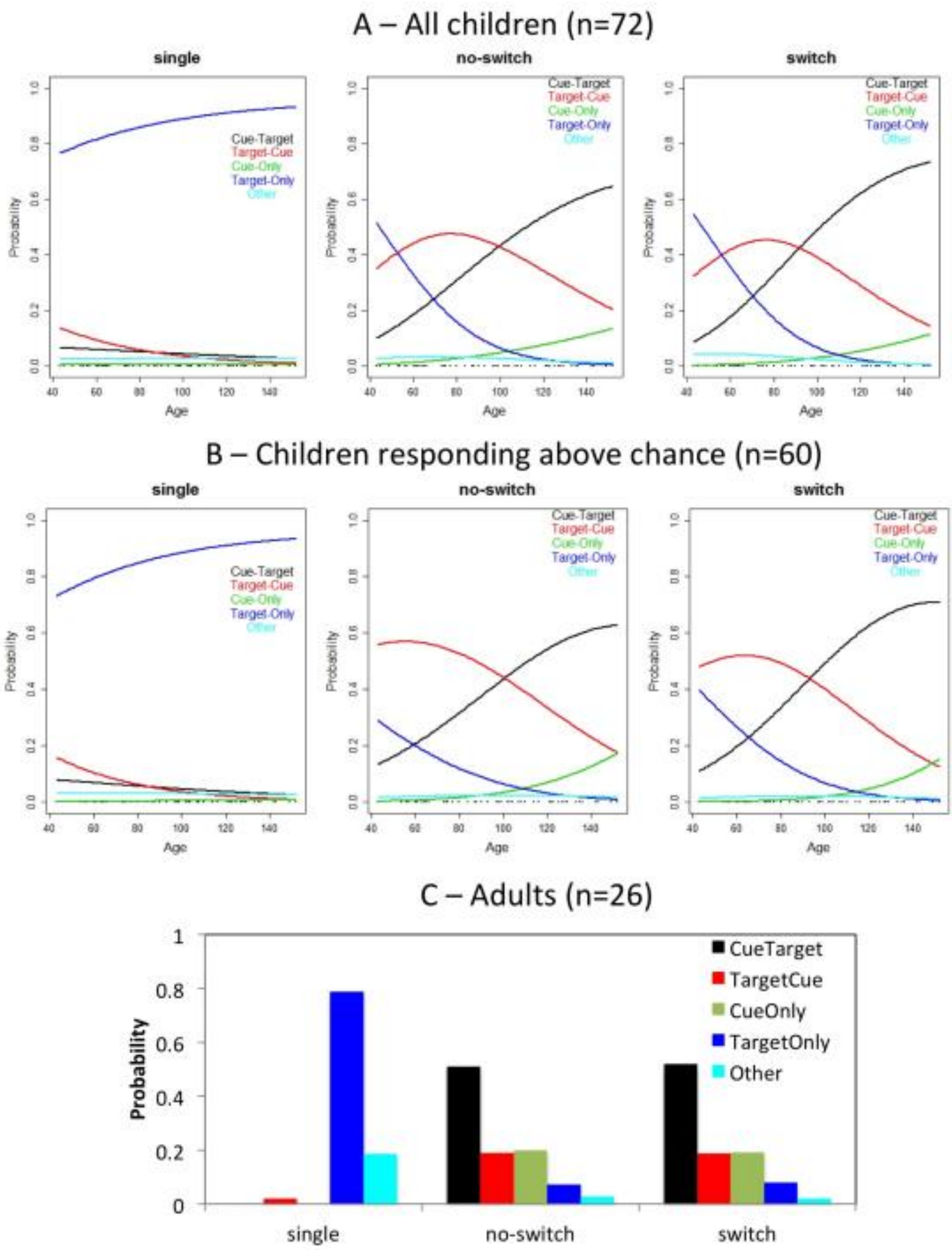

Figure. 3. Probability of each gaze pattern as a function of trial type and age in months in children (A, B), and as a function of the trial type in adults (C). Both children and adults gazed only at the target in single trials. In no-switch and switch trials, *Target-Cue* patterns decreased whereas *Cue-Target* patterns increased with age during childhood (A). This pattern was even more pronounced after excluding

children who responded at chance in the mixed-task block (B). Like older children, adults mostly started with the cue before fixating the target on switch and no-switch trials (C).

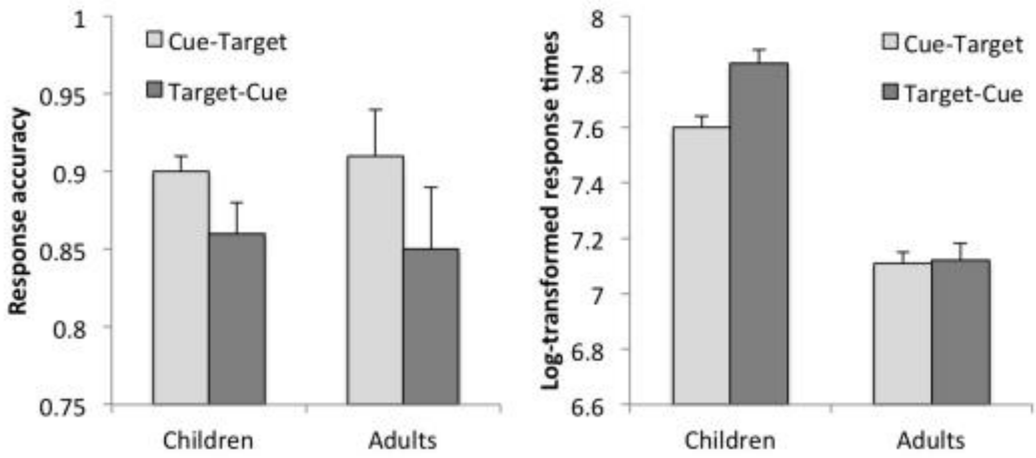

Figure 4. Response accuracy and log-transformed response times for *Cue-Target* and *Target-Cue* patterns in the mixed-task block. Both children and adults performed better when they gazed at the cue first than when they started with the target. Error bars represent standard errors.